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Self-assembled formation of quantum dots during InGaAlAs quantum well growth

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There exists a strong interest in direct techniques for fabrication of semiconductor structures with reduced dimensionallity: quantum wires and quantum dots (QDs). Currently the most developed technique to create QDs is related to self-organized formation of uniform three-dimensional islands at crystal surfaces in Stranski-Krastanow growth [1-4]. Alternative approach for nanostructure fabrication represents spontaneous phase separation in semiconductor alloys [see e.g. 5]. Recently, it was found that strained InGaAs layers grown by Metal-Organic Vapor Phase Epitaxy (MOVPE) in a GaAs matrix also exhibit lateral compositional modulations [6]. The luminescence properties of these structures, however, are similar to those in quantum wells, except of some peculiarities in luminescence polarization and lasing. In this paper we show, that spontaneous phase separation effects are much more pronounced in case of strained InGaAlAs layers in an AlGaAs matrix and result in formation of QDs demonstrating very large localization energies.

Structures investigated in this work were grown by molecular beam epitaxy (MBE) or MOVPE technologies on the GaAs (001) semiinsulating substrates. MOVPE structure comprised of a 1 μm-thick $Ga_{0.5}Al_{0.5}As$ buffer, an active layer and a 0.15 μm-thick $Ga_{0.5}Al_{0.5}As$ cap layers. Active layer represented single 10 nm $In_{0.12}As_{0.63}Al_{0.25}As$ layer confined by 0.3 μm-thick $Ga_{0.75}Al_{0.25}As$ layers on both sides. MBE structure comprised of a 0.05 μm $Ga_{0.35}Al_{0.65}As$ buffer, an active layer, and a 0.05 μm $Ga_{0.35}Al_{0.65}As$ cap layers. Active region was similar to the MOVPE case except the average In concentration was 10%. Both structures had 10 nm GaAs cap layers to prevent oxidation of Al containing layers. The growth temperature for the active region was in the both cases 500°C.

Low temperature photoluminescence (PL) spectra at different excitation densities of the MBE structure is presented on the Fig. 1. At low excitation density one can see three peaks in the energy range (1.1–1.55 eV) significantly shifted towards longer wavelength as expected for peak energy for uniform 10 nm-thick $In_{0.12}As_{0.63}Al_{0.25}As$ layer (see the QW transition energy marked by arrow). As the structure can be observed only for the case of InGaAlAs layers, one can conclude that these peaks are due to In-rich domains formed by phase separation effects during alloy growth. Multi peaks character of the emission spectrum can be explained by coexistence of domains having different size or composition QDs by sizes. Increase in the excitation density results in appearance of PL lines at energies corresponding to transitions in the uniform 10 nm-thick $In_{0.12}As_{0.63}Al_{0.25}As$ layer (1.76 eV) and in GaAlAs barrier (1.86 eV), respectively. At very high excitation level the PL peaks from QDs saturate due to finite density of

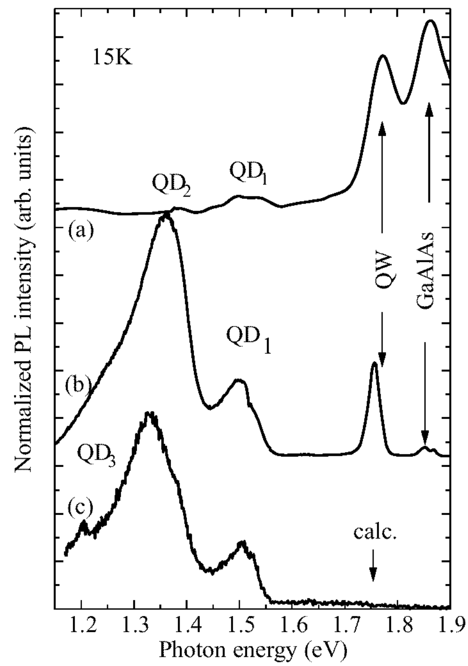

Fig 1. PL spectra for MBE structure measured at 17 K at different excitation level (a) 1 MW/cm^2, (b) 200 W/cm^2, (c) 50 mW/cm^2).

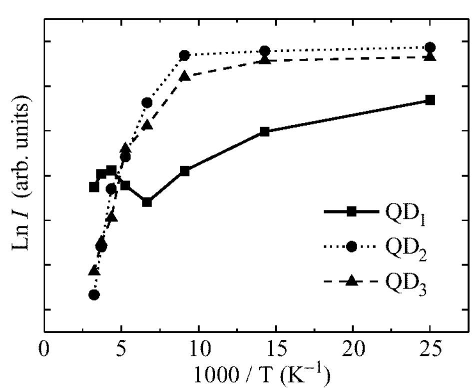

Fig 2. Temperature dependencies of integrated PL intensity for three different QD. Excitation density is 200 W/cm^2.

In-rich domains and the QW and the GaAlAs barrier luminescence become dominant. Temperature dependencies of integrated intensities of different QDs lines are presented in Fig. 2. At temperatures higher than 150 K there occurs efficient carrier redistribution between different types of the QDs. It shows significant hopping of carriers between different types of QDs at elevated temperatures.

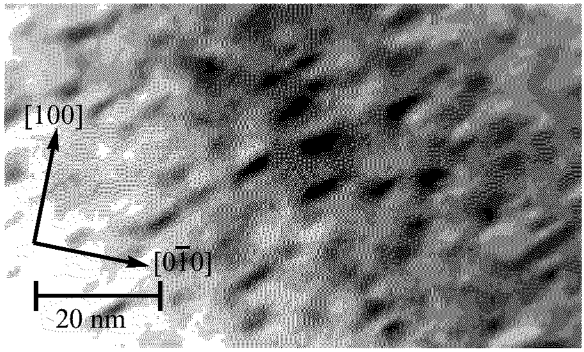

Fig 3. TEM image of MBE structure imaged under the strong beam condition. Note formation of elongated compositional domains.

Figure 3 shows a bright-field (200) plan-view transmission electron microscopy (TEM) image of the MBE structure. One can see QDs having characteristic lateral sizes 15 nm by 7 nm and prolonging in the [110] direction. Density of these QDs is about 2×10^{11} cm^2. TEM investigations of the MOVPE structure show formation of QDs with lateral sizes less than 10 nm, the contrast modulation is weaker and the dots have symmetric shape. Density of QDs in this case is about 10^{11} cm^2. In PL spectra these dots result in appearance of a broad line placed at lower energies (1.40–1.63 eV) than the QW transition energy (1.665 eV). This agrees with smaller size and In composition as compared to MBE case.

To conclude, we demonstrate that InGaAlAs layers with very low average indium composition effectively decompose to In-rich nanoscale domains during epitaxial growth. The resulting quantum dots have significant localization energies as follows from temperature dependencies of the corresponding PL lines.

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